Evaluation and Improvement of High-resolution Mesoscale Models on Boundary Layer Simulations Using Ground-based Observations

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LONG-TERM GOAL

The long-term goal of the proposed work is to improve the physical parameterizations and wind forecast from high-resolution COAMPS. This is done through analyses of a large amount of data from a dense measurement network located the coastal Florida peninsula and through testing and evaluation of COAMPS simulations.

OBJECTIVES

The objectives of this year's work were to in-depth analyses of the tower observations to calculate turbulence fluxes and surface roughness length and to select representative cases for future observation evaluation of COAMPS simulations.

APPROACH

This project involves extensive data handling and analyses and model testing using high-resolution COAMPS. Our general approach is to identify model issues through data analyses and model-observation inter-comparison. Improvements of model physics should be a result of these analyses and testing. Eventually, improved model physics will be tested in COAMPS and evaluated against the observations. Within this project, we will also investigate methods for objective model evaluation, particularly for high-resolution mesoscale models.

Investigators in this project include Dr. Qing Wang (PI) and Dr. Kostas Rados who is a visiting professor at NPS supported by this project. A NPS M.S. student, Capt. M. Ellis (USAF) and a visiting student intern also worked on this project. Lt. Col. Karl Pfeiffer (USAF), military faculty at Information Sciences Department at NPS, assisted in obtaining data and data collection information from various AF units. Collaboration efforts with Dr. Melinda Peng at NRL is an important part of

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this project which include COAMPS physical parameterization development and testing and identifying the path for eventual transition of the results to operational COAMPS.

WORK COMPLETED

1. Extensive data processing of the tower measurements from the Kenny Space Center (KSC)/Cape Canaveral Air Force Station (CCAFS) in 2008. The entire dataset contains continuous measurements by a suite of over 200 wind, temperature, humidity, and pressure sensors attached to 46 instrumented towers distributed across a 1,200-km^2 region on the east coast of the Florida Peninsula. Data processing involves reading, formatting the original data and re-writing data in time sequence for each level at each tower, and eliminating bad data sections. Data accessing, consolidation of data collection and site information, and initial data quality checking was a major technical challenge to this project.

2. For towers with multiple levels of measurements, turbulent momentum flux, sensible heat flux, latent heat flux, and surface roughness height were calculated. Quality control of the results is essential to this project because of the coarse precision of the wind data, which was output at integer knots. A set of usable data criteria is thus defined to include wind no less than 2 ms^{-1}, and wind speed difference between the two levels selected for flux calculation exceeding 0.5 ms^{-1} . The flux calculating algorithm involves two levels of wind, temperature, and specific humidity (when available) measurements and utilizes Monin-Obukhov similarity theory involving thermal stability of the surface layer. Flux calculations were made for all towers with at least two levels of measurements.

3. Initial data analyses were made for case selection purpose. We decided to work on two types of cases: one involves passage of sea breeze front (SBF) with moderate wind and wind direction changes, the other case is from the passage of tropical storm Fay with relatively strong wind and significant wind direction change. Wind direction variation is a key factor in our case selection in order to identify variations of surface roughness length (SRL) change in response to various upwind surface conditions.

4. Extensive analyses were made on variations of surface roughness length as a function of wind direction due to heterogeneous surface characteristics in the surrounding area.

5. COAMPS simulations of tropical storm Fay were evaluated using the large amount of tower data.

RESULTS

Surface fluxes and surface roughness length calculation from tower measurements: Figures 1 and 2 show an example of the observed quantities and calculated fluxes for the northeast sensors at the lowest levels (referred to as levels 1 and 2) of Tower 0313 on 2-5 May 2008. Here, wind, potential temperature, and specific humidity shown in both figures were used to calculate the sensible heat flux (SHF), latent heat flux (LHF), frictional velocity (u_*) and surface roughness length (z_0). On the flux plots, thermally unstable (red) and stable (blue) conditions are determined by the difference between the indicated levels, which clearly show the daytime unstable and nocturnal stable surface stratifications. Diurnal variations in all variables are also clearly seen with reasonable magnitude of surface sensible and latent heat fluxes. On days 122-124, progression of the synoptic-scale pattern induced a gradual veering from southeasterly to southwesterly flow, with higher wind speeds observed

during the daylight hours than at night. The calculated surface layer u_* in Fig. 2 seems to reflect this change in wind reasonably well. During most of this 4-day period, $z_0 \leq 0.5$ m, and u_* ranges between 0.2 and 0.6 ms^{-1}. However, between midnight and sunrise of day 123 and for most of the first half of day 124, unreasonably large z_0 values are calculated. During both of these periods, relatively low wind speeds (< 2 ms-1) are observed. In addition, large temporal variations in z_0 are noted during these periods. Similar trends in roughness length are observed throughout the year during periods of low wind speeds, often occurring overnight. Calculated roughness lengths during these periods are considered unphysical for two reasons. First, the wind speed precision (0.5 ms^{-1}) results in large relative error in wind velocity, which is even more so in low wind conditions. Secondly, applications of the Monin-Obukhov similarity theory is questionable in low wind speed conditions, especially for nocturnal stable boundary layers in which turbulence is usually weak and intermittent. Thus low-wind conditions, defined as wind speed <2 ms^{-1} are excluded in the flux analyses.

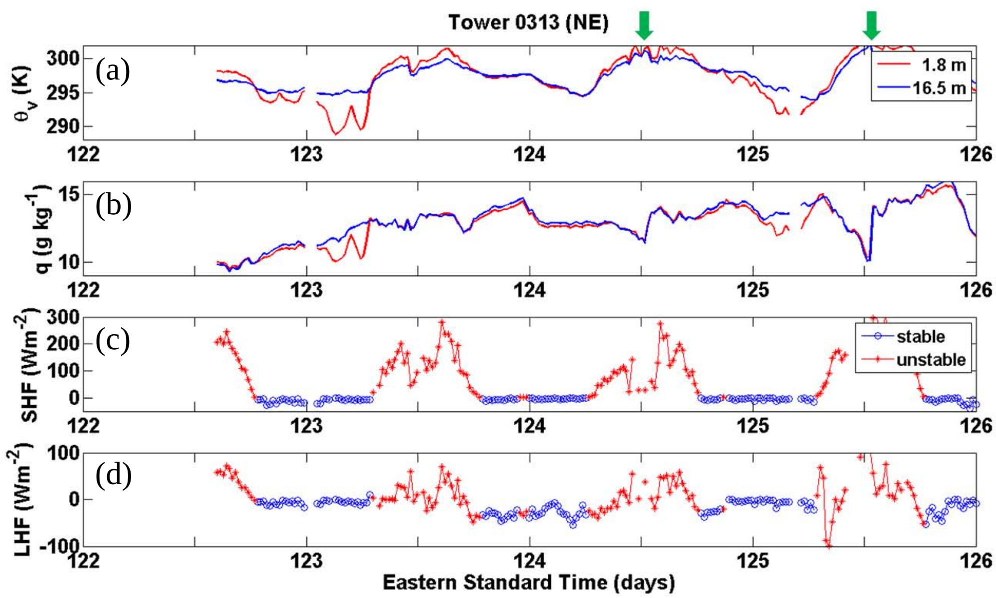

Figure 1. Temporal variations of observed (a) virtual potential temperature (θ_v, K) and (b) specific humidity (q, g kg^{-1}) and calculated (c) sensible and (d) latent heat fluxes in Wm^{-2} from the northeast sensors at temperature levels 1 and 2 of Tower 0313 on 2-5 May 2008.

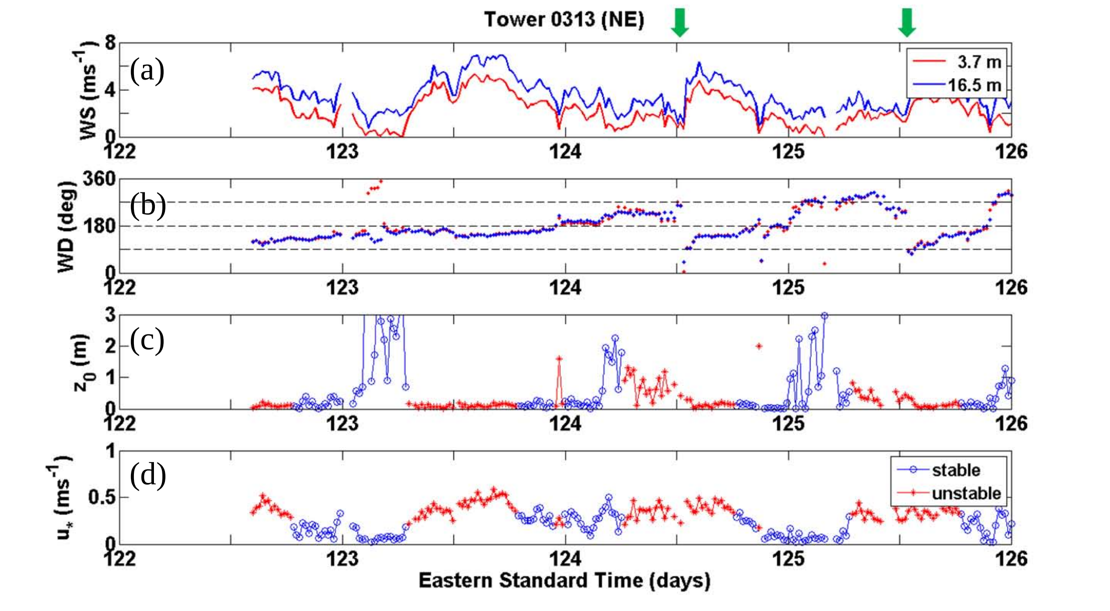

Figure 2. Temporal variations of observed (a) wind speed (WS, ms^{-1}) and (b) wind direction (WD, degrees) and calculated (c) roughness length (z_0 ,m) and (d) friction velocity (u_* , ms^{-1}) from the northeast sensors at wind levels 1 and 2 of Tower 0313 on 2-5 May 2008.

In Figs. 1 and 2, green arrows indicate the passage of two SBFs around noon on days 124 and 125 (4-5 May 2008). SBF passage is most readily indicated by the sudden backing of the wind direction from southwest to southeast and the rapid increase in q. In addition, wind speeds at the 16.5-m sensor increase from about 2 ms^{-1} to 6 ms^{-1}, and temperatures at both levels gradually fall following SBF passage. Figure 3 below contains vertical profiles of θ_v, q, wind speed, and wind direction observed from the northeast sensors of Tower 0313 at 4-hour intervals beginning at 0500 EST on 4 May 2008. Such plots are useful for evaluating the evolution and vertical variation of these measured fields and will be used in the future to evaluate COAMPS simulations for the SB cases. In Fig. 3a, at 0500 EST (about 1 hour prior to sunrise), the surface layer is thermally stable. With daytime heating, the lowest layers become increasingly unstable. Around 1300 EST, a SBF passed the tower location. The wind profiles at 1300 EST indicate that the SBF had passed the sensors at wind levels 1-4, but had not yet passed the higher levels of the tower. The uniform directional profile shown before and after SBF passage was typically observed on days affected by these coastal wind circulations. In Fig. 3c, logarithmic wind profiles that fit to observations from the lowest two levels are plotted on the wind speed profiles in blue dashed lines.

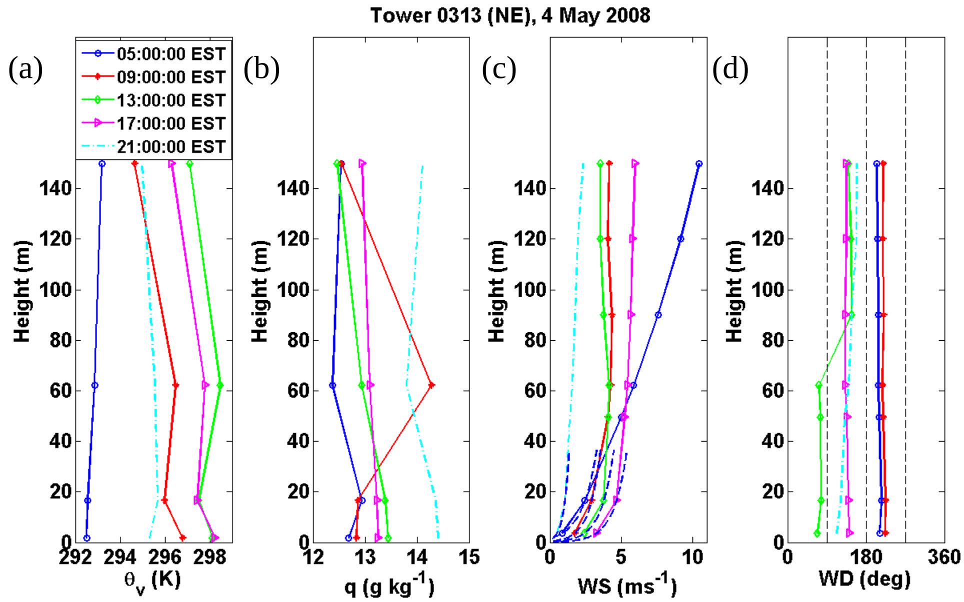

Figure 3. Vertical variation of observed (a) virtual potential temperature (θ_v), (b) specific humidity (q), (c) wind speed (WS), and (d) wind direction (WD) from the northeast sensors of Tower 0313 on 4 May 2008.

Roughness length variation in response to coastal wind circulations: To investigate this subject, we chose the measurements between 1-4 June 2008 with a series of coastal wind circulations occurred at CCAFS. Although daily mesoscale sea breezes are a common occurrence in the region throughout the warm season, this period was particularly selected for its lack of significant convective activity in the vicinity of CCAFS to ensure the validity of Monin-Obukhov surface-layer similarity for flux calculations.   Here an example is given using measurements from Tower 0006, a launch critical tower ~600 m from the shoreline. Figures 4a, 4b, 4c,and 4d show the wind, roughness length, and u_* variation during the selected period calculated using measurements from levels 1 and 2. Same calculated variables can be also obtained using other levels. Figure 4e shows the surroundings of Tower 0006 that consists of mainly shrubs and small trees, the largest of which (using a qualitative shadow analysis technique) lie in sectors 40°-120°, 150°-190°, and 330°-350°. Within a 50-m radius of Tower 0006, an "X"-shaped area of cleared ground contains the attachments for the tower's guy wires. Variations of this clearing are present at each launch critical tower.

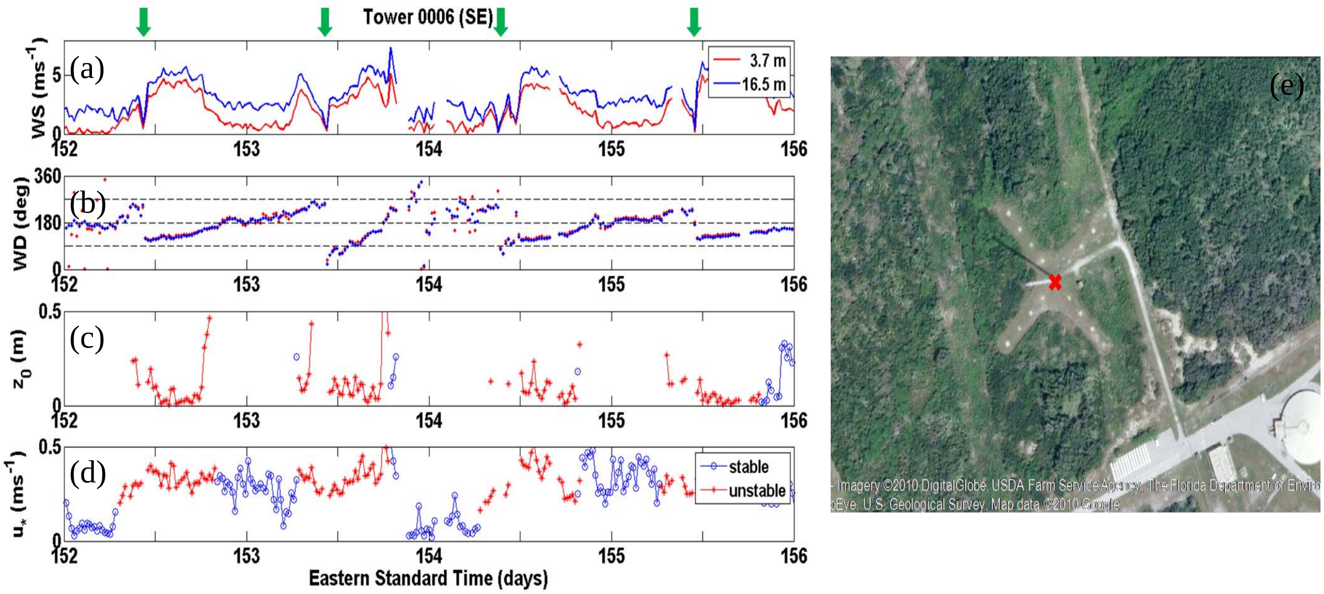

Figure 4. (a),(b),(c), and (d) Same as in Fig. 2, except for the SB front case between 1-4 June, 2008. (e) Satellite photograph of Tower 0006 and immediate surroundings. Red "X" marks the tower location. Image ©2010 Google.

In Fig. 4, wind speed and direction indicate the passage of four SBFs before noon each day (indicated by green arrows). Following each SBF, wind speeds increase and the flow backs rapidly from the southwest to the southeast, followed by a gradual veering to the southwest during the remainder of the day and overnight. Maximum wind speeds of about 5 ms^{-1} at both levels occur following the SBF each afternoon, and the weakest winds are observed around midnight. The calculated friction velocity u_* ranges between 0.1 and 0.5 ms^{-1}, a typical range for surface layers over land at these wind speeds. The calculated z_0 is mostly less than 0.25 m.

On all four days, the lowest z_0 values for levels 1 and 2 were recorded when the wind direction was from sector 120°-150°, which is seen in Fig. 4e to roughly correspond to an opening in the trees connecting ground in the immediate vicinity of Tower 0006 to close-cut grass and roads near buildings located 200 m southeast of the tower. At approximately this distance in any other direction from the tower, more numerous low shrubs and trees are present, and when the flow is from these sectors, higher z_0 values are calculated for levels 1 and 2. Similar results are seen from z_0 calculated from other levels of measurements. The relationship between z_0 and wind direction in varying stability conditions are best seen in Fig. 5 which contains polar plots of z_0 averaged over 15° sectors for the entire year 2008 for the southeast sensors at levels 1 and 2 (Fig. 5a) and levels 2 and 3 (Fig. 5b). The tower location is the pole for these plots, and wind direction is the azimuthal coordinate. Line segments connecting the average z_0 value (plotted on the center radials of each 15° sector) form the blue outline in each plot. These " z_0 roses" compare reasonably well to the satellite images of Tower 0006 (Fig. 4e).

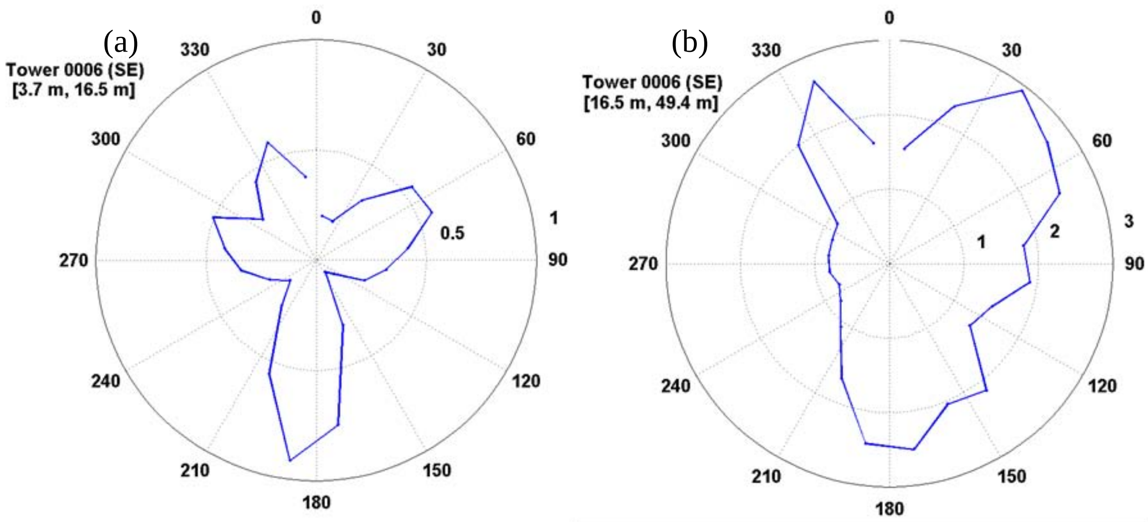

Figure 5. Polar plots of calculated roughness length z_0 averaged over each 15° sector from the southeast sensors at (a) wind levels 1 and 2 and (b) wind levels 2 and 3 of Tower 0006 for 1 January to 31 December 2008.

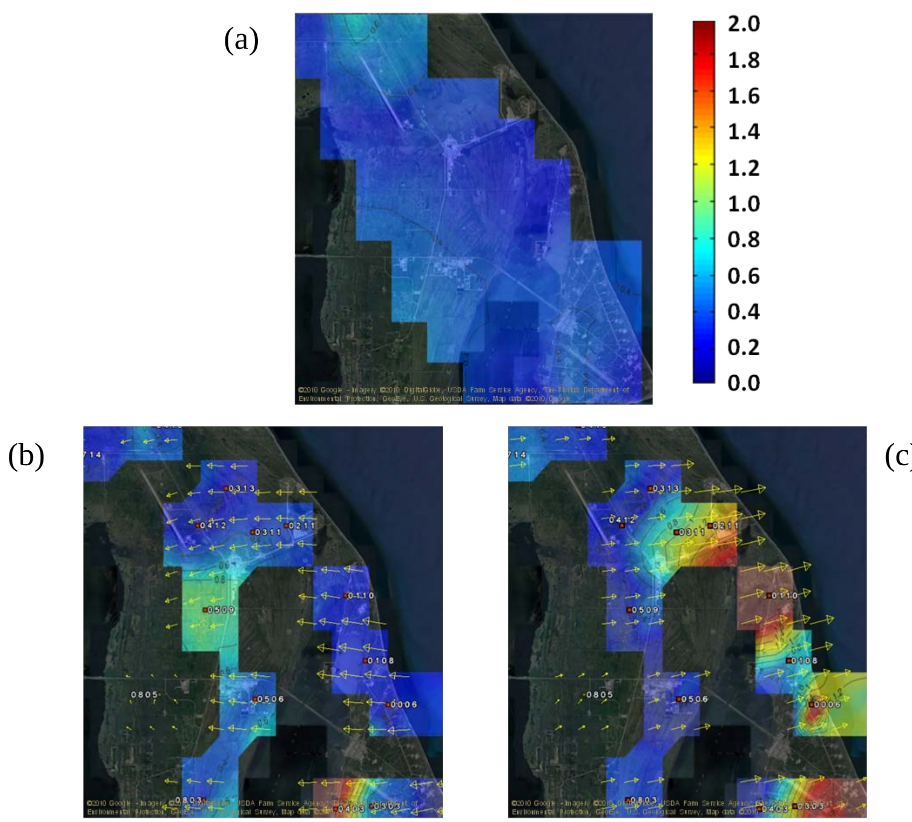

Figure 6. Contour plots of roughness length from (a) COAMPS and 16.5-m wind observations and calculated z_0 from at (b) 0000 EST and (c) 1800 EST on 20 August 2008. Image ©2010 Google.

In Fig. 5a, the "X" pattern is discernible, though the branches of the "X" in the polar plot corresponding to larger z_0 values associated with areas of trees and shrubs between the cleared areas visible on the satellite photograph. In Fig. 5b, sectors with larger z_0 correspond to wind directions from forested areas situated 100-300 m from the tower. At the same distance to the west, the landscape appears to be smoother, and z_0 values corresponding to westerly winds are lower. Same analyses were made at other towers and similar results were obtained.

Roughness length variation in tropical storm Fay: Tropical storm Fay resulted in significant wind direction change in high wind conditions and provide a perfect opportunity for evaluating the effect of upstream surface condition on the locally measured z_0 over heterogeneous conditions. The result is summarized in Fig. 6 where the calculated z_0 from all available towers are shown as contour plots at different stages of Fay with opposite wind direction. In this figure, satellite imagery of the Cape Canaveral region is overlain by interpolated z_0 values contoured at 0.2 m intervals. As previously noted, z_0 is a fixed quantity at each grid point in mesoscale models, including COAMPS. Fig. 6a shows the COAMPS z_0 field, ranging from about 0.2-0.6 m. It is seen that roughness height over the surface of the Banana River are low within the limit of model resolution. At the resolution of COAMPS, subgrid-scale surface heterogeneities such as those considered in this study are not discernible. Figure 6b shows a contour plot of z_0 using observations from the lowest two tower levels at about 0000 EST on 20 August 2008, when the center of Fay was located southwest of CCAFS. Arrows indicate the speed and direction of the 16.5-m wind. Figure 6c is a contour plot of winds from 18 hours later, when Fay had moved northeast of CCAFS and winds were offshore. Figure 6a shows that for tower locations near the coast, z_0 values were comparable to the fixed COAMPS z_0 field in the strong onshore flow conditions. Figure 6c, on the other hand, with similar wind speed but oposite wind direction, much higher z_0 values are obtained. An area in the center of both plots was excluded in order to avoid interpolating across a large area devoid of observations. Compared to the COAMPS gridded data field, relatively few observation sites were used to construct these contour plots; however, values near the higher-density tower locations carry a high degree of confidence, such as those along the immediate coastline and in the cluster of towers located at the top of the images. Apparently, the observed temporal and spatial variation of roughness length is not represented by COAMPS, which depends upon land surface type only and is independent of wind flow. Relating the roughness length to the surface-layer dynamics would involve a complex blending of the effects of various IBLs over heterogeneous regions, and this relationship would be necessarily dependent upon wind speed and direction.

IMPACT/APPLICATIONS

The results from the second-year research of this project revealed, in great detail, the variations of surface roughness length in response to wind direction over heterorogeous surfaces. This variation is not represented by the fixed value of z_0 currently in COAMPS. The impact of the such simplification should be further examined using model results and new approach of z_0 representation in mesoscale models should be investigated.

TRANSITIONS

The results of this project will potentially help to evaluate and improve the surface flux parameterizations in mesoscale models for simmulations over inhomogeneous land surfaces.